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COMPUTER-AIDED ENGINEERING ENVIRONMENT FOR CONTROLLED MECHANICAL SYSTEMS

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A computer-aided engineering environment for the design and analysis of computer controlled mechanical systems is defined, and a prototype environment is demonstrated. The overall integrated environment includes systems for 3D geometric modeling and animation, multibody system dynamics, finite element analysis, and control system design. The integration of a multibody system dynamics program IMP with the control system design program MATRIXx is demonstrated. Transfer functions from the multibody system model, together with mathematical models of any electrical, pneumatic, and hydraulic components, are used in MATRIXx for control system synthesis. The controller architecture and parameters are specified in block diagram form and converted to a real-time program through an automatic code generator in MATRIXx. This program is downloaded to a microprocessor for controlling the actual, physical plant; In the computer-aided engineering environment of this report, the controller program with any nonmechanical component models included is combined with the original IMP nonlinear mechanical system model. The dynamic response of this complete system is studied to verify the controller design for this nonlinear, more realistic mechanical model. (KR)

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INTRODUCTION

Digital controls are rapidly emerging as attractive design options for mechanical machinery and vehicle systems. The need to consider digital controllers as a design option is dictated by the ever stringent constraints on design while attempting to meet the increasing expectations of design functionality and performance. The feasibility and the economic viability of this opportunity are being stimulated by the expanding commercial availability of off-the-shelf microprocessors for a broader range of application specifications. Further possibilities for digital controllers are made possible by the availability of relatively inexpensive and reliable sensors, actuators, and input/output devices.

An increasing number of products and systems in a variety of end use applications are being influenced by the digital control design option, for example: 1. consumer products such as washing machines, lawn mowers, other appliances; 2. industrial machinery such as mining equipment, conveyors/feeders, turbomachinery; 3. on and off road vehicle systems including suspensions, brakes, steering, power trains; 4. manufacturing equipment including machine tools, robots, end effectors; and 5. defense/aerospace systems, among others. A trend towards the increased deployment of digital controls in mechanical systems can be very beneficially enhanced by a cohesive, rational, and broad-based computer-aided engineering environment for the design of these controlled mechanical systems. A computer-aided engineering (CAE) environment for the modeling, design, and control of mechanical systems of the type mentioned above is described in this report. This environment for controlled mechanical systems will be referred to by the acronym CAEE-CMS.

Controlled Mechanical Systems

Typically, a controlled mechanical system is comprised of the following subsystems:

- A multibody, dynamic system characterized by geometrically constrained, nonlinear (i.e., large displacement) behavior. Further, structural flexibility, lumped springs and dampers, disturbances, and a variety of control forces and torques must be included in the model of the mechanical system, as appropriate. The passive spring and damper elements may be nonlinear, in addition to producing nonlinear geometric effects on the system behavior.

- A broad variety of sensors must be modeled and included in the system, such as resolvers, tachometers, rate gyros, accelerometers, and others.

- Similarly, actuators and their dynamic models must be included in the system design process. For example, the actuators may include electrical, hydraulic, or pneumatic systems, or some combination of these.

- For digital control systems, the effects of D/A's, A/D's, and computation and transmission delays must be included in the system design considerations.

Computer Aided Engineering (CAE) Tools

In recent years, a number of CAE tools have been developed and accepted in industrial design practice for the design of the various subsystems which comprise a controlled mechanical system. Relevant CAE tools for the various subsystems include:

- Geometric modeling tools and the associated interactive graphics for the design and modeling of mechanical components. Many of the commercial CAD systems fall in this category, particularly if they allow modeling of solids and surfaces. The primary use of these systems for the CAEE-CMS is in the computation of component mass properties, the creation of a mechanical model, and a graphics links to finite element modeling tools. A realistic animation of the system's dynamic motion for a visual check of the system behavior under controlled conditions for various system disturbances can be depicted. Detection of collisions between various parts and their interference checks is a particularly beneficial capability in a geometric modeling tool for evaluating the spatial motions of the mechanical system.

- A variety of finite element modeling (FEM) and finite element analysis (FEA) tools are available; many are interfaced to commercial geometric modeling tools while some have their own geometric modeling utilities. The use of the FEM/FEA tools within the context of a CAEE-CMS is in the modeling of structurally flexible modal components of the multibody system. The resulting modal characteristics (i.e., the natural frequencies and mode shapes of the appropriately retained modes within the frequency range of interest for a specific body) can then be incorporated within the system model of the multibody system by the modal synthesis technique or one of its variants (refs 1 and 2). In those situations where such modal synthesis techniques are applicable, mostly for vibratory response around a reference position of the mechanical system, the coupling between the FEM/FEA tools and a multibody analysis tool can be accomplished (ref 3). For situations where the interface between modal modeling and the multibody dynamics system model may result in approximations due to "linearization too early" errors, a combined derivation of the component mass and stiffness matrices has been developed by starting with the element displacement fields and using the system velocities and accelerations for creating a system model (refs 4 and 5).

- A number of CAE tools for multibody dynamic analysis are commercially available, for example, IMP (ref 6), ADAMS (ref 7), and DADS (ref 8). New codes, largely based upon Kane's method (ref 9) are also becoming available, some using symbolic processing of Kane's formulation to produce customized codes for the specific system's equations of motion (ref 10).

- A variety of CAE tools for control system analysis, synthesis, and design are commercially available for personal computers, workstations, and mainframes. Examples include: CC, Ctrl-C/Model-C, autocon, $MATRIX_X$, design engine, among others (ref 11).

These various CAE tools constitute a well established tool kit for the modeling, simulation, design, and control of dynamic mechanical systems. The CAEE-CMS (fig. 1) is an integrated design environment where selected tools from each of the above categories can be used in concert for the design of controlled mechanical systems. The following tools were selected for creating the integrated environment:

- **$MATRIX_X$**. This system incorporates classical and modern control design procedures for the design, synthesis, and analysis of control strategies. Component models of electrical, hydraulic, or pneumatic actuators and models of mechanical subsystems can be created in $MATRIX_X$ to investigate such control strategies as PID, LQG/LTR, Adaptive, and H-infinity, among others. $MATRIX_X$ assists the designer with time and frequency domain analysis and design techniques, and is a versatile tool for control system design. One of the unique features of $MATRIX_X$ is its AUTOCODE function. AUTOCODE produces an optimized source code in FORTRAN, C, or ADA from the block diagram representation of the control laws. This source code can be compiled, linked, and downloaded to an on-board computer as a controller to drive the actual physical system with appropriate A/D and D/A facilities to interact with the sensors and actuators of the physical system.

- **IMP (Integrated Mechanisms Program)**. The IMP system performs the kinematic, static, and dynamic analysis of multibody mechanical systems. It can also be made to output transfer functions and simulated sensor values.

- **GMS (Geometric Modeling System)**. The GMS program is a 3D solids modeling program to model the physical components of a mechanical system. The GMS program can also be used to computer the mass, mass moments of inertia, and section properties of the modeled components. The associated software package called LYNX2 acts as a preprocessor and postprocessor for IMP. Shaded image animation of the dynamic behavior of a mechanical system as computed by IMP is displayed by the LYNX2 system on the Silicone Graphics, Inc. IRIS computer graphics workstation (ref 12).

- **COSMOS/M**. COSMOS/M Is a finite element analysis program which is used to conduct static stress and dynamic analyses of flexible structural components (ref 3).

The standard control system design and synthesis techniques are based on linear system theory. In most cases, multibody mechanical systems are nonlinear; therefore, a transfer function representation of the mechanical system, linearized about a reference position, is needed. This linearized, s-domain representation of the system provides the structural model parameters for the integration between IMP and $MATRIX_X$ for producing the FORTRAN code for the designed control laws is another primary integration requirement which resulted in the selection of $MATRIX_X$ for the integrated environment. The GMS and IMP programs are presently interfaced in LYNX2, and the COSMOS/M to CAEE-CMS interface is slated for future work. Therefore, the remainder of this report will focus on the integration process between IMP and $MATRIX_X$ to demonstrate the integrated environment.

INTEGRATION OF IMP AND $MATRIX_X$

A conceptual block diagram for the IMP and $MATRIX_X$ integration is shown in figure 2. The specific details of the block diagram will become clear during the following discussion.

Transfer Functions

The concept of transfer functions of multibody mechanical systems is similar to the transfer functions for linear models but with some important differences. For a simple spring-mass-damper linear system, the equation of motion:

$$M \cdot \frac{d^2}{dt^2} \cdot X(t) + c \cdot \frac{d}{dt} \cdot X(t) + K \cdot X(t) = F(t) \tag{1}$$

This differential equation in the time-domain can be converted to the s-domain:

$$[M \cdot s^2 + C \cdot s + K] \cdot X(s) = F(s) \text{ or } \frac{X(s)}{F(s)} = \frac{1}{M \cdot s^2 + C \cdot s + K} \tag{2}$$

where

$s = j\omega$ and $J = \sqrt{-1}$

The expression of equation 2 is normally referred to as the transfer function relating the displacement X(s) to the force F(s) and can be represented by a sum of complex numerators and denominators as:

$$\frac{X(s)}{F(s)} = \frac{N_1}{s - D_1} + \frac{N_2}{s - D_2} \tag{3}$$

Where N_1 and N_2 are complex conjugates of each other, and the denominator terms D_1 and D_2 are also complex conjugates of each other. D_1 and D_2 are also the system eigenvalues. For this simple case, assuming an underdamped system,

$$D_1 = \frac{-C}{2 \cdot M} + j \cdot \frac{\sqrt{4 \cdot K \cdot M - C^2}}{2 \cdot M} \qquad D_2 = \frac{-C}{2 \cdot M} - j \cdot \frac{\sqrt{4 \cdot K \cdot M - C^2}}{2 \cdot M} \tag{4}$$

$$N_1 = -j \cdot \left[\frac{1}{\sqrt{4 \cdot K \cdot M - C^2}} \right] \qquad N_2 = j \cdot \left[\frac{1}{\sqrt{4 \cdot K \cdot M - C^2}} \right] \tag{5}$$

For a single degree of freedom system, equation 3 shows that two numerator and denominator ratios are obtained; these are complex conjugate pairs, i.e., N_1 and N_2, D_1 and D_2. For an n degree of freedom system, the general form of the transfer function is:

$$\frac{X(s)}{F(s)} = \frac{N_1}{s - D_1} + \frac{N_2}{s - D_2} + \frac{N_3}{s - D_3} + \frac{N_4}{s - D_4} + \dots + \frac{N_{2n-1}}{s - D_{2n-1}} + \frac{N_{2n}}{s - D_{2n}} \tag{6}$$

Where N_1 and N_2, D_1 and D_2 are complex conjugate pairs; N_3 and N_4, D_3 and D_4 are complex conjugate pairs, and so on. There are 2n ratios in the transfer function of equation 6.

Multibody, constrained mechanical systems are inherently nonlinear systems because of the large geometry changes during their motion. The concept of transfer functions is applicable to linear systems only. Therefore, for the multibody systems, the transfer functions can only be valid for small vibratory motions around an operating point, such as a static equilibrium position. Further, the spring-mass-damper models are greatly idealized models. In the multibody systems of the type considered in this report, a typical model may be represented by a collection of links, joints, springs, dampers, and excitations of forces and motions (fig. 3). Although IMP is a 3-dimensional analysis system, figure 3 is shown as a 2-dimensional system for clarity in presenting the concepts without having to interpret the spatial complexity. In this system, BASE is a fixed body with respect to the XY inertial frame; TANK slides relative to BASE in the X direction; L1 is connected to TANK by a revolute joint; L2 is connected

by a revolute joint to L1 and to L3 by another revolute joint; L3 is connected to L4 by a revolute joint, while L4 is connected by a prismatic joint to TANK. The symbolic names of the various revolute and prismatic joints are also defined in figure 3. The kinematic degrees of freedom of this system is 3; the IMP sy stem automatically identifies the degrees of freedom by an algorithm based on the rank of the instantaneous system geometry matrix. IMP also identifies the appropriate generalized coordinates, or motion variables, as the independent variables at the instantaneous configuration of the mechanical system.

For the system shown in figure 3, if the X and the Y positions of the tip are to be controlled so that the tip position remains at the reference position X. and Y., the control is to be provided by a DC motor at the revolute joint R1. If the disturbance to this system results from the motion excitation at the sliding joint DIST, the motion would reduce the kinematic degrees of freedom of the system from 3 to 2. Therefore, the various transfer functions for this system can be computed by IMP for the vibration response of the various motions of interest:

$$R_1 = \theta_{1.} + \theta_1(t) \qquad X = X. + X(t) \qquad Y = Y. + Y(t) \tag{7}$$

and the various transfer functions are the complex ratios:

$$\frac{\theta_1}{T} = \frac{N_1}{s - D_1} + \frac{N_2}{s - D_2} + \frac{N_3}{s - D_3} + \frac{N_4}{s - D_4}$$

$$\frac{\theta_1}{DIST} = \frac{A_1}{s - D_1} + \frac{A_2}{s - D_2} + \frac{A_3}{s - D_3} + \frac{A_4}{s - D_4}$$

$$\frac{X}{T} = \frac{B_1}{s - D_1} + \frac{B_2}{s - D_2} + \frac{B_3}{s - D_3} + \frac{B_4}{s - D_4} \tag{8}$$

Similarly for Y/T, X/DIST, and Y/DIST.

These transfer functions provide the building blocks for the block diagram description of a dynamic system, including the transfer function representation of the sensors and of the actuators.

If a position control system is to be design with a DC motor used as the actuator at the R1 joint, the position sensors could be placed at any location, although good control design practice would dictate the location of the sensor ideally at the place of control, in this case, the rotation of joint R1. As an example, the reference position $\theta_{1.}$ corresponding to the tip point position X., Y. can be directly controlled. A position sensor, such as a resolver, can provide the position feedback. A typical block diagram representation of the control system is shown in figure 4. The transfer functions are computed at the

reference, which in most cases would be a position of static equilibrium. As an example, for a specific set of design parameters for the system of figure 3, the transfer function relating the θ_1 displacement to the torque T computed by IMP is:

$$\frac{\theta_1}{T} = \frac{0.000358 + j \cdot 0.0001053}{s - (-0.595 + j \cdot 16.985)} + \frac{0.000358 + j \cdot 0.0001053}{s - (-0.595 - j \cdot 16.985)}$$

$$+ \frac{-0.000358 + j \cdot 0.00777}{s - (-3.3165 + j \cdot 34.807)} + \frac{-0.000358 - j \cdot 0.00777}{s - (-3.3165 - j \cdot 34.807)}$$

and the transfer function relating the θ_1 displacement to a harmonic displacement at the distrubance input of the tank is:

$$\frac{\theta_1}{DIST} = \frac{(0.0017449 + j \cdot 0.0010235) + (-0.0000214 + J \cdot 0.00000134) \cdot s^2}{s - (-0.595 - j \cdot 16.985)}$$

$$+ \frac{(0.0017449 - j \cdot 0.0010235) + (-0.0000214 - j \cdot 0.00000134) \cdot s^2}{s - (-0.595 - j \cdot 16.985)}$$

$$+ \frac{(-0.0017449 - j \cdot 0.043708) + (0.0000214 - j \cdot 0.0016884) \cdot s^2}{s - (-3.3165 + j \cdot 34.807)}$$

$$+ \frac{(-0.0017449 + j \cdot 0.043708) + (0.0000214 + J \cdot 0.0016884) \cdot s^2}{s - (-3.3165 - j\, 34.807)}$$

State Representative Models

Transfer functions generated by IMP provide one method for communicating a mechanical system model to the control design system. Some procedures for control system synthesis require a state space representation of the mechanical system. A state space model, by definition, requires the use of the minimum possible number of state variables to define the system state. A state space model of the mechanical system can be derived by the following alternative methods.

State Model from Transfer Function

For an n degree of freedom mechanical system, an IMP transfer function is of the form:

$$\frac{O(s)}{I(s)} = \frac{N_1}{s - D_1} + \frac{N_2}{s - D_2} + \frac{N_3}{s - D_3} + \cdots + \frac{N_{2n}}{s - D_{2n}} \qquad (9)$$

A typical pair is:

$$\frac{N_1}{s - D_1} + \frac{N_2}{s - D_2} = \frac{A_1 + j \cdot B_1}{s - [C_1 + j \cdot D_1]} + \frac{A_1 - j \cdot B_1}{s - [C_1 - j \cdot D_1]} = \frac{P_1 \cdot s + Q_1}{s^2 + R_1 \cdot s + T_1} \qquad (10)$$

where

$$P_1 = 2 \cdot A_1 \qquad\qquad R_1 = -2 \cdot C_1$$

$$q_1 = -2 \cdot [A_1 \cdot C_1 + B_1 \cdot D_1] \qquad\qquad T_1 = C_1^2 + D_1^2 \qquad (11)$$

Therefore, the IMP generated transfer function can be represented as a summation of n second order systems:

$$\frac{O(s)}{I(s)} = \frac{P_1 \cdot s + Q_1}{s^2 + R_1 \cdot s + T_1} + \frac{P_2 \cdot + Q_2}{s^2 + R_2 \cdot s + T_2} + \ldots + \frac{P_n \cdot s + Q_n}{s^2 + R_n \cdot s + T_n} \qquad (12)$$

The linear system characterized by the transfer function of equation 12 can be represented as:

$$\frac{O(s)}{I(s)} = \frac{O(s)_1}{I(s)} + \frac{O(s)_2}{I(s)} + \ldots + \frac{O(s)_n}{I(s)} \qquad (13)$$

where

$$O(s) = O(s)_1 + O(s)_2 + \ldots + O(s)_n \qquad (14)$$

Again, a typical term in the summation of equation 13 is

$$\frac{O(s)_1}{I(s)} = \frac{P(s)_1 + Q_1}{s^2 + R_1 \cdot s + T_1} \qquad (15)$$

therefore,

$$O_1 + R_1 \cdot O_1 + T_1 \cdot O_1 = P_1 \cdot I + Q_1 \cdot I \qquad (16)$$

Define two state variables for this second order system,

$$q_1 = q_2 \qquad\qquad q_2 = -R_1 \cdot q_2 - T_1 \cdot q_1 + I \qquad (17)$$

and for the output equation, select

$$O_1 = P_1 \cdot q_2 + Q_1 \cdot q_1 \qquad (18)$$

These state variables lead to the original second order system. A state representation of the second order system of equation 15 is:

$$\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} O & 1 \\ -T_1 & -R_1 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} O \\ 1 \end{bmatrix} I \tag{19}$$

and

$$O_1 = \begin{bmatrix} Q_1 & P_1 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \tag{20}$$

For an n degree of freedom system, a state characterization from an IMP generated transfer function is:

$$\begin{bmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ \cdot \\ q_{2n} \end{bmatrix} = \begin{bmatrix} O & 1 & & & & & \\ -T_1 & -R_1 & & & & \bigcirc & \\ & & O & 1 & & & \\ & & -T_2 & -R_2 & & & \\ & & & & \ddots & & \\ & \bigcirc & & & & O & 1 \\ & & & & & -T_n & -R_n \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ \cdot \\ q_{2n} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ 1 \end{bmatrix} \tag{21}$$

and, since $O = O_1 + O_2 + O_3 + \ldots + O_n$

$$O = [Q_1 \ \ P_1 \ \ Q_2 \ \ P_2 \ldots Q_n \ \ P_n] \begin{bmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ \cdot \\ q_{2n} \end{bmatrix} \tag{22}$$

Also, since $O = O_1 + O_2 + \ldots + O_n$

$$O_i = [-P_i \cdot T_i \; [Q_i - P_i \cdot R_i]] \begin{bmatrix} q_{2i-1} \\ q_{2i} \end{bmatrix} + P_i \cdot I \qquad (23)$$

$$i = 1, 2, \ldots, n$$

$$O = [-P_1 \cdot T_1 \; [Q_1 - P_1 \cdot R_1] \ldots -P_n \cdot T_n \; [Q_n - P_n \cdot R_n]] \begin{bmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ \cdot \\ q_{2n} \end{bmatrix}$$

$$+ [P_1 + P_2 + P_3 \ldots P_n] \, I \qquad (24)$$

Resulting in

$$\begin{bmatrix} O \\ O \end{bmatrix} \quad \begin{bmatrix} q_1 & P_1 & \ldots & q_n & P_n \\ -P_1 \cdot T_1 & [q_1 - P_1 \cdot R_1] & & -P_n \cdot T_n & Q_n - P_n \cdot R_1 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ \cdot \\ q_{2n} \end{bmatrix}$$

$$+ \; [P_1 + P_2 + . ^{\circ} . . + P_n] \, I \qquad (25)$$

Equations 21 and 25 comprise a state characterization of the mechanical system. For each output of interest in a mechanical system, it is possible to derive the corresponding state characterization. Since each output results in a 2n set of state variables as shown in equation 21, a multiple output system will result in a set of state variables consisting of more than the minimum number required to define the system state. A matrix rank based approach to identify the minimum subsystem from the original system matrix of equation 21 is available to $MATRIX_X$ based on the algorithm described in reference 15. This procedure in $MATRIX_X$ can be used to define the minimal subsystem and the relationship between the original and the new space.

A potential problem in using transfer functions to create the state space models is that, depending upon the specific outputs chosen for the transfer functions, it is possible to either completely miss or to minimize the importance of one or more modes of the system. With appropriate care, however, it is possible to create a valid state representation of the mechanical system from IMP generated transfer functions.

State Model Directly from IMP

Another method for state space characterization of the mechanical system is to directly use the generalized coordinate based dynamical formulation originally used by IMP to compute the transfer functions. For an n degree of freedom mechanical system, IMP selects the appropriate generalized coordinates based upon a coordinate partitioning scheme. This scheme (ref 16) identifies an independent set of generalized coordinates which produces numerically well-conditioned computations. For an n degree of freedom, with input force, torque, or displacement I, the IMP generated state space model is of the form:

$$\underset{(2n \times 1)}{\{q\}} = \underset{(2n \times 2n)}{[A]} \{q\} + \underset{(2n \times 1)}{\{B\}} I \qquad (26)$$

The outputs of interest, such as the x,y,z displacements of a point or the displacement within a joint, are related to the generalized coordinates by algebraic relationships which are computed by IMP. For example, for the x,y displacements of the tip point and for the θ_1 displacement in the system of figure 3,

$$\begin{bmatrix} x \\ y \\ \theta_1 \end{bmatrix} = \begin{bmatrix} c_1 & c_2 & 0 & 0 \\ d_1 & d_2 & 0 & 0 \\ e_1 & e_2 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \qquad (27)$$

where c_1, c_2, d_1, d_2, e_1, e_2 are computed by IMP at the reference position. Equations 26 and 27 comprise a state space representation of the mechanical system.

Control System Design in MATRIX$_X$

The state space representation of the mechanical system is then combined with the transfer function representations of the sensors and the actuators to form a complete block diagram model of the dynamic system. The block diagram is completed by visually interconnecting the transfer functions and assigning external inputs/outputs using the system build function of MATRIX$_X$. Based on the model, most classical and modern design methodologies can be used to develop a discrete time controller. This controller is connected to the IMP-derived linear model to validate its performance and

robustness characteristics. One of the key features of this process is that $MATRIX_X$ can produce an optimized FORTRAN, C, or ADA computer program based on the controller block diagram which can be compiled, linked, and downloaded to a microprocessor. The computer program, generated by AUTOCODE and called SCHEDULE, contains the necessary information on such parameters as sampling rate, number of inputs, and the number of outputs. The SCHEDULE program samples the inputs at the frequency defined by the designer and calculates control outputs based on the closed form control law.

IMP Simulation of Controlled System

The SCHEDULE program and the associated routines produced by $MATRIX_X$ will now be used to control the original IMP model which produced the linearized transfer functions of the mechanical system. The objective now is to carry out nonlinear time-history simulations of the controlled mechanical system with the SCHEDULE program acting as the digital controller.

The integration of IMP with the $MATRIX_X$ generated SCHEDULE program requires the resolution of the following issues:

- The time integration procedure in IMP is a variable step, stiff system integration scheme specifically developed for internal IMP calculations. IMP's integration time step is adjusted to minimize the estimated error of the numerical integration process at each time step. The sampling time for the digital controller SCHEDULE is a constant time interval selected during the control design process. The strategy developed for the integrated use of IMP and the SCHEDULE program is to assign the sampling interval of SCHEDULE as the upper limit of the numerical integration time step. If the integration time step is adjusted by IMP to be less than the sample interval (i.e., between two samples), the values of the input sensors and the outputs are assigned constant values of the most recently sampled inputs and computed outputs. This interface is identical to the behavior of a typical digital controller where the inputs and the outputs hold their values until a new sample is taken.

- The SCHEDULE program requires the instantaneous samples of inputs, or sensors, to compute the values of the outputs based on the control law built into the SCHEDULE program. IMP has a well-developed vocabulary in a user oriented language for the description of a mechanical system. The inputs and outputs required by the SCHEDULE program at each sampling instant are directly defined within the IMP problem model. For example, figure 5 shows the IMP problem model for the two mass, three springs system used as the illustrative example in this report. The SCHEDULE program in this case needs four inputs: position of mass M1, velocity of mass M1, position of mass M2, and the velocity of mass M2. The output from the SCHEDULE program is the control force on the mass M1; the force is named f1. To define the

corresponding sensors and actuators in IMP, standard keywords are used. The VALUE statement is necessary to interrogate IMP for specific joint or point variables (i.e., accelerations, velocities, positions, torques, or forces). These variables are convenient IMP key words known as POSITION, VELOCITY, FORCE, etc.

The interface between the IMP system and the SCHEDULE program is by a standard USER subroutine. This is the subroutine which accesses the IMP data base at the time instant of the sample; the VALUE statements and their input numbers (e.g., I1, I2, I3, etc.) provide the required definitions of the various sensor variables to the USER routine. These values are passed by the USER routine to the SCHEDULE program. The output from the SCHEDULE program, in this case O1, is assigned to the instantaneous value of the force f1. This is shown in figure 5 as the two IMP statements:

```
    value (O1)  = user (IO1)
data force (f1) = O1
```

The USER routine also checks the specific time when the requests for VALUES are initiated by IMP. As indicated, IMP requests these values at the adjusted integration time step; the USER routine then decides whether to take the additional sample and call SCHEDULE or to return the values from the previous sample based upon whether the sample interval has elapsed from the previous sample, as explained above. The USER routine, therefore, acts as a traffic manager for the interchange of data between IMP and SCHEDULE.

The IMP key word vocabulary and its capability to perform algebraic computations written in FORTRAN provide a powerful vehicle to model a variety of sensor inputs. Some examples already completed are: resolver, tachometer, rate gyro, angular acceleration sensor, position sensor, velocity sensor, and line of sight sensor.

Software for IMP and MATRIX$_X$ Integration

A series of FORTRAN modules have been written to fully automate the processing, data, and code transfer between IMP and MATRIX$_X$ and vice versa. The following describes the modules and their functions:

- Plotting Module. Uses the MATRIX$_X$ plotting capabilities to produce plots and graphs of IMP time-history results (i.e., displacements, velocities, accelerations, forces, and torques versus time). The IMP generated output files are converted to the MATRIX$_X$ file format for loading into MATRIX$_X$. The MATRIX$_X$ plotting capability is routinely used during the control system design and analysis process, and it was felt that a consistent format of IMP and MATRIX$_X$ plots would enhance the overall CAEE-CMS.

- Transfer Function Module. Conversion of the IMP generated transfer f unctions into a state characterization.

- IMP User Function Module. A standard IMP USER function to: extract sensor data at each instant of time; interface with $MATRIX_X$ generated control code (SCHEDULE); and produce nonlinear time-history dynamics.

- Schedule Modification Module. A software module to: perform minor editing of the $MATRIX_X$ generated SCHEDULE and associated code; compile SCHEDULE and associated code, including some dummy routines to replace the hardware calls in an actual plant controller; and link the compile code with IMP to produce the executable version.

These software modules comprise a key part of the CAEE-CMS.

ILLUSTRATIVE EXAMPLE

The complete integration of IMP and $MATRIX_X$ is illustrated in figure 5. The displacement of mass M1 is X_1, and of mass M2 is X_2. A control force F1 is applied at M1. This system is a linear system and the CAEE-CMS advocated in this report is directed toward nonlinear mechanical systems of the type shown in figure 3. However, this model simplifies the validation of the CAEE-CMS and illustrates the following steps of the integrated design process.

1. Development of the IMP model for this system and the computation of the transfer functions: $X_1(s)/F_1(s)$ and $X_2(s)/F_1(s)$.

2. Generation of the state characterization model with eight states in this case.

3. $MATRIX_X$ procedure is required to convert the state characterization model into a minimal space representation. The minimal procedure produces a state space representation with four states in this case.

4. Design of a compensator for this model. The model was discretized and an LQG controller was designed. The overall block diagram for the controlled mechanical system is shown in figure 6. A block with a time delay of 0.01 seconds is included in the model to account for the computational time delay of the controller.

5. AUTOCODE generation of the controller program SCHEDULE which represents the finalized control law. This SCHEDULE program is edited, compiled, and linked with the IMP program.

6. Validation of the digital controller running on the full nonlinear IMP model (linear in this case). The open and closed loop responses of this system to nonzero initial conditions, i.e., mass M1 displaced 1 inch to the right and mass M2 displaced 2 inches to the right is shown in figure 6. The results from IMP with the SCHEDULE code as the controller are identical to the results obtained from a simulation performed in $MATRIX_X$ using the same digital controller operating on the continuous plant model.

CONCLUSIONS

A prototype computer-aided engineering environment for controlled mechanical systems (CAEE-CMS) has been demonstrated.. The environment includes the commercially available subsystems for multibody dynamics (IMP), geometric modeling and animation (GMS/LYNX2), and control system design ($MATRIX_X$). The concept of transfer functions is central to the CAEE-CMS. This report documents the current status of work in progress. The CAEE-CMS (fig. 1) is the ultimate environment toward which the current research is progressing.

The CAEE-CMS is presently being used for several applications. A helicopter gun turret system (fig. 7) suffers significant disturbance inputs from helicopter vibration, gun firing, and structural flexibility of the gun supporting structure and gun barrel. The dynamics of this system can vary significantly due to gun pointing, helicopter configuration, and flying conditions. The CAEE-CMS is being used to study the dynamic behavior of this system and develop control algorithms to improve the accuracy of this weapon system.

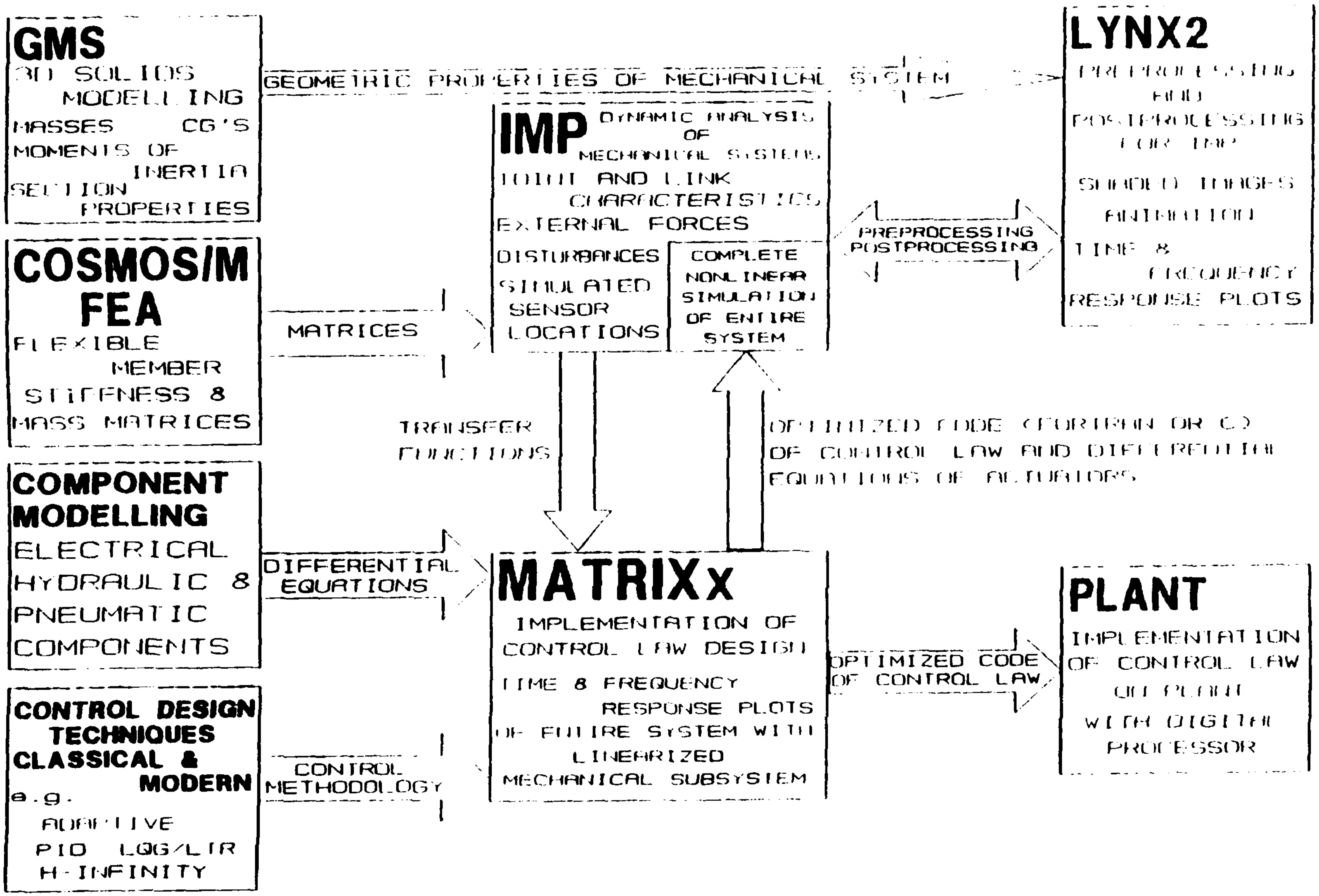


Figure 1. Computer aided engineering environment

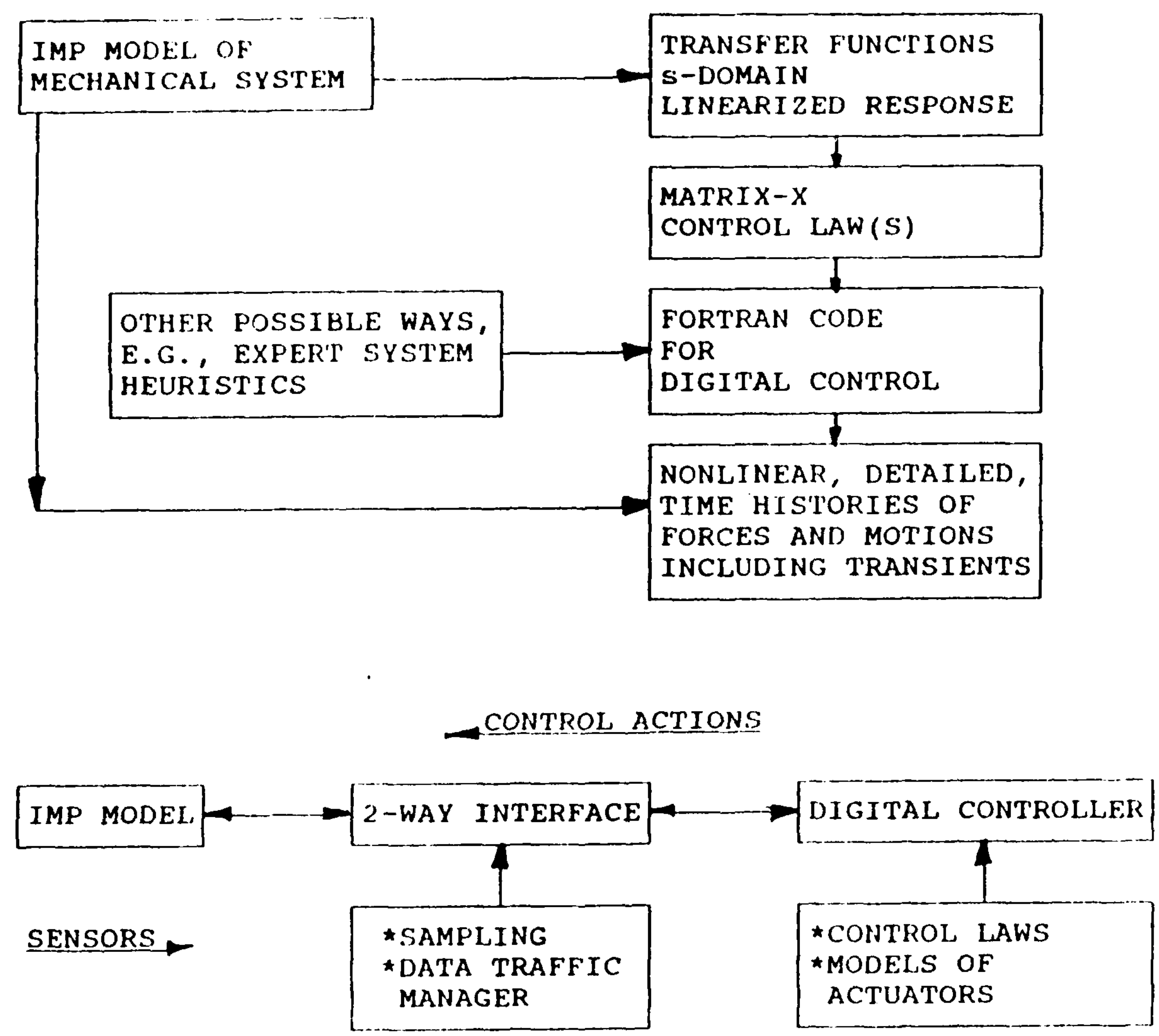


Figure 2. Concept of IMP and $MATRIX_x$ integration

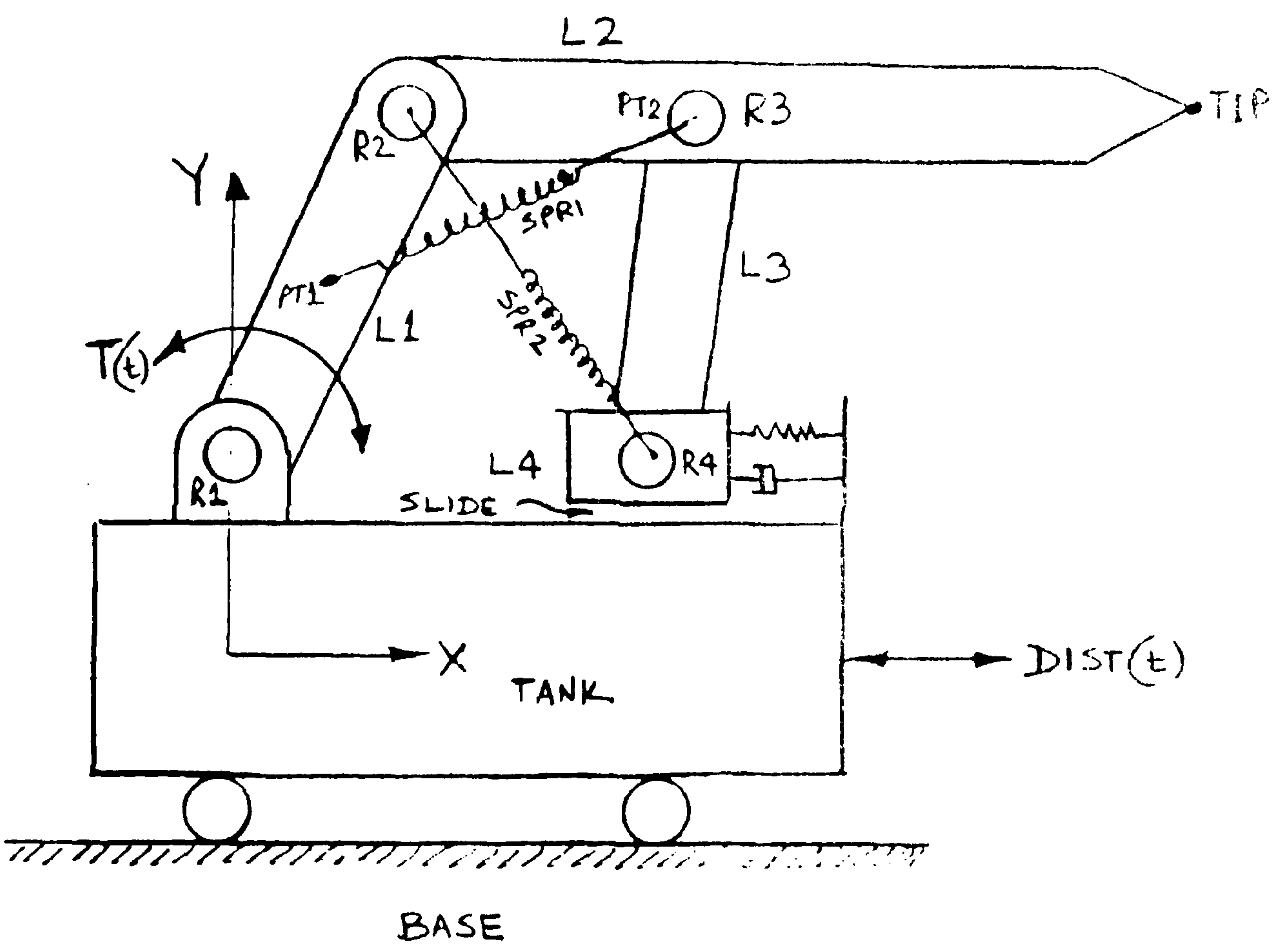


Figure 3. Example of a constrained multibody system

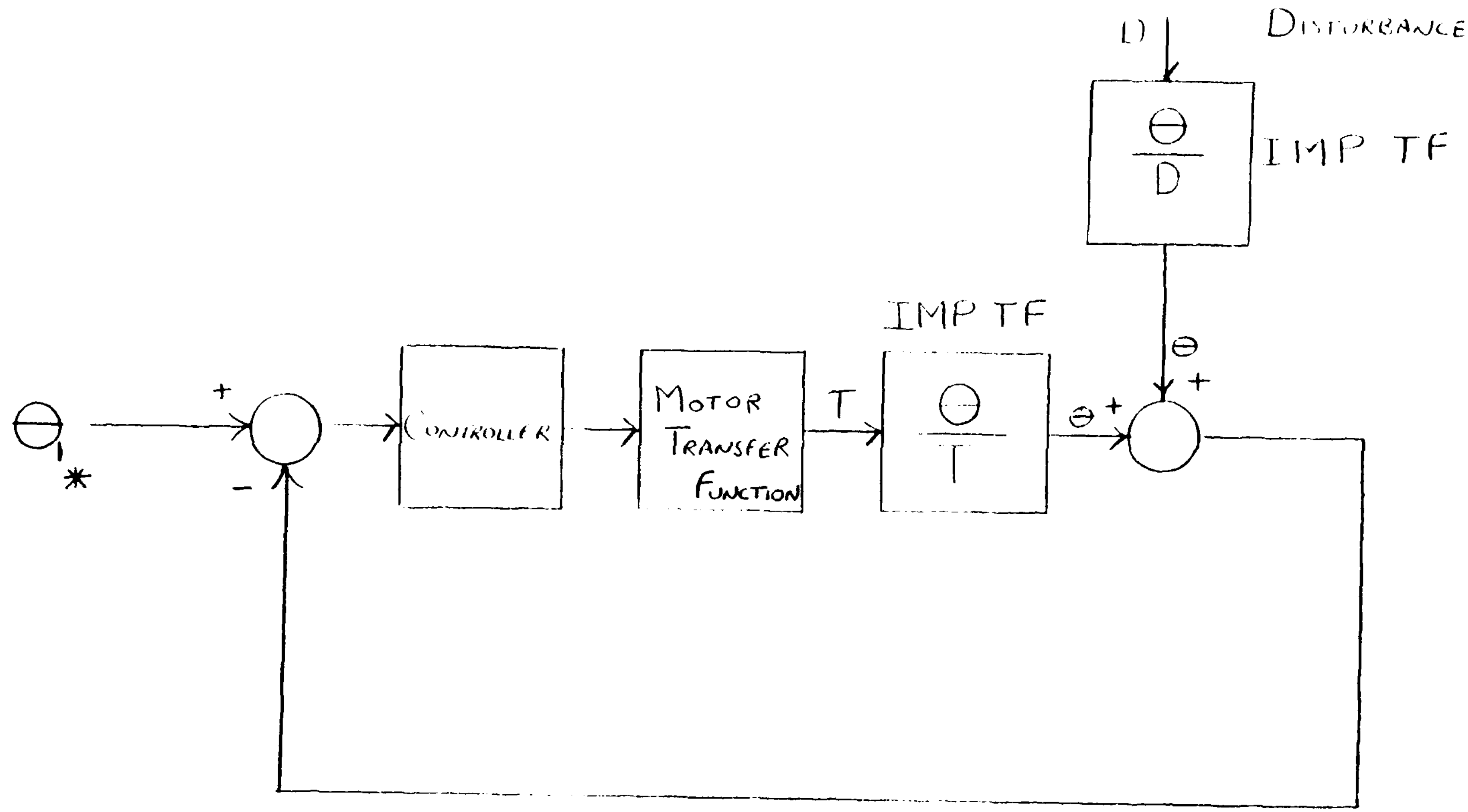
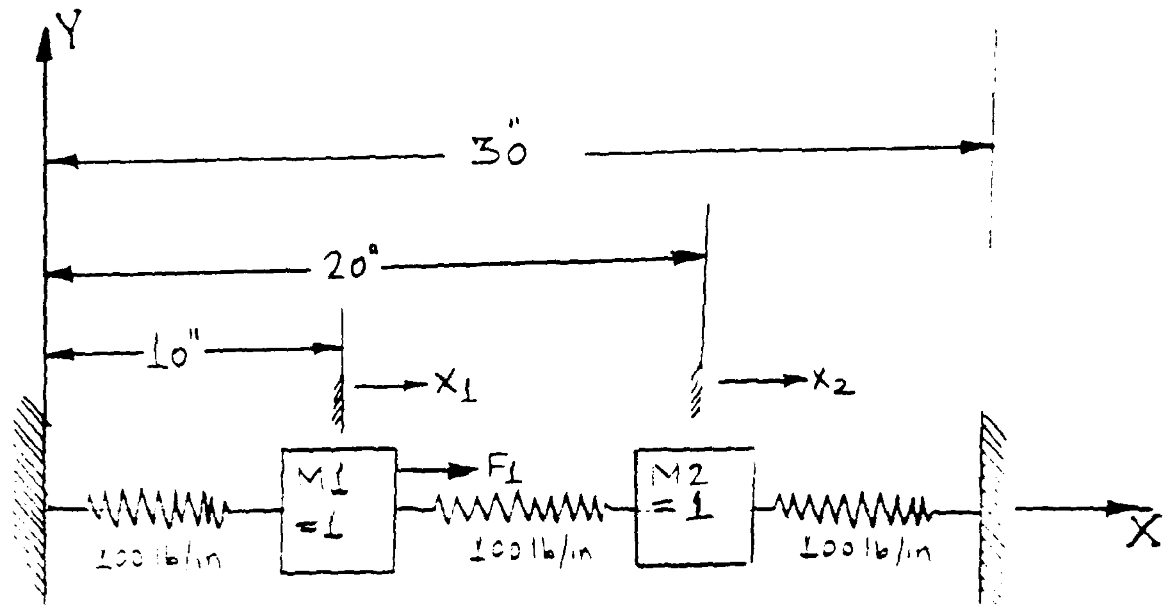


Figure 4. General block diagram representation of position control system for the constrained multibody system. (Note the role of IMP generated transfer functions.)




```
$$
$$ Two Mass System Connected with Springs
$$
$$ Sept 19,1989
$$
find,dynamics
ground=base
prism(base,masl)=p1
data link base p1=0,0,0;1,0,0;0,0,1
data link masl,p1=10,0,0;11,0,0;10,0,1
data spring(p1)=100,10
prism(base,mas2)=p2
data link,base,p2=30,0,0;20,0,0;30,0,1
data link,mas2,p2=20,0,0;10,0,0;20,0,1
data spring(p2)=100,10
point(masl)=pt1
data point(pt1,p1)=0,0,0
point(mas2)=pt2
data point(pt2,p2)=0,0,0
spring(pt1,pt2)=sp1
data spring(sp1)=100,10
unit mass=1
data mass(masl,p1)=1;0,0,0
data mass(mas2,p2)=1;0,0,0
$$
value(I1)=position(pt1,1)
value(I2)=velocity(pt1,1)
value(I3)=position(pt2,1)
value(I4)=velocity(pt2,1)
value(O1)=user(IO1)
force(pt1,pt1,pt2)=f1
data force(f1)=O1
list,position(pt1,pt2)
data time=10,.01,.01
data,ic(p1)=11,0
data,ic(p2)=6,0
return
```

Figure 5. System for demonstration of IMP and MATRIX$_X$ integration with IMP program

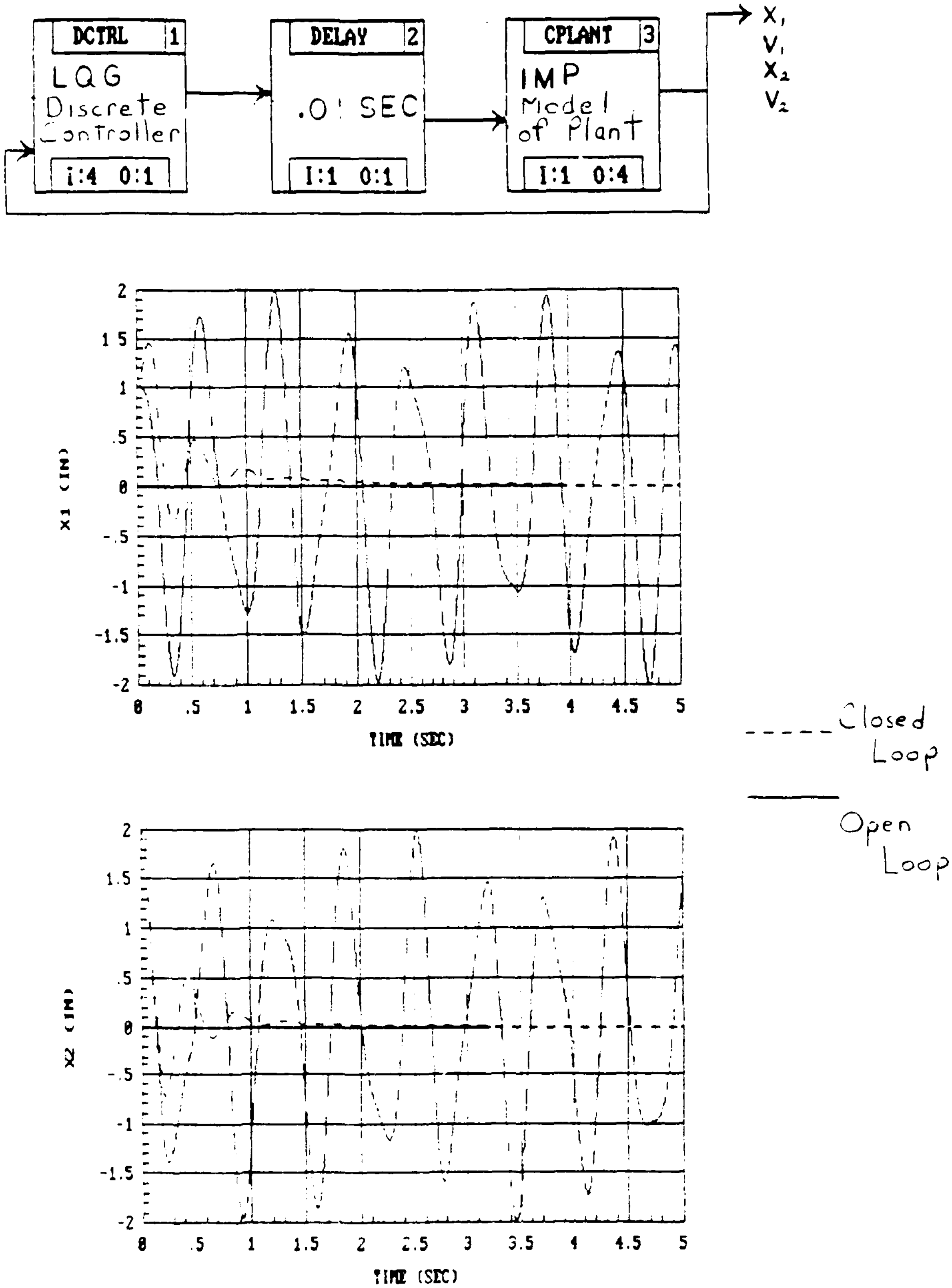


Figure 6. Results of MATRIX$_X$/IMP analysis of system

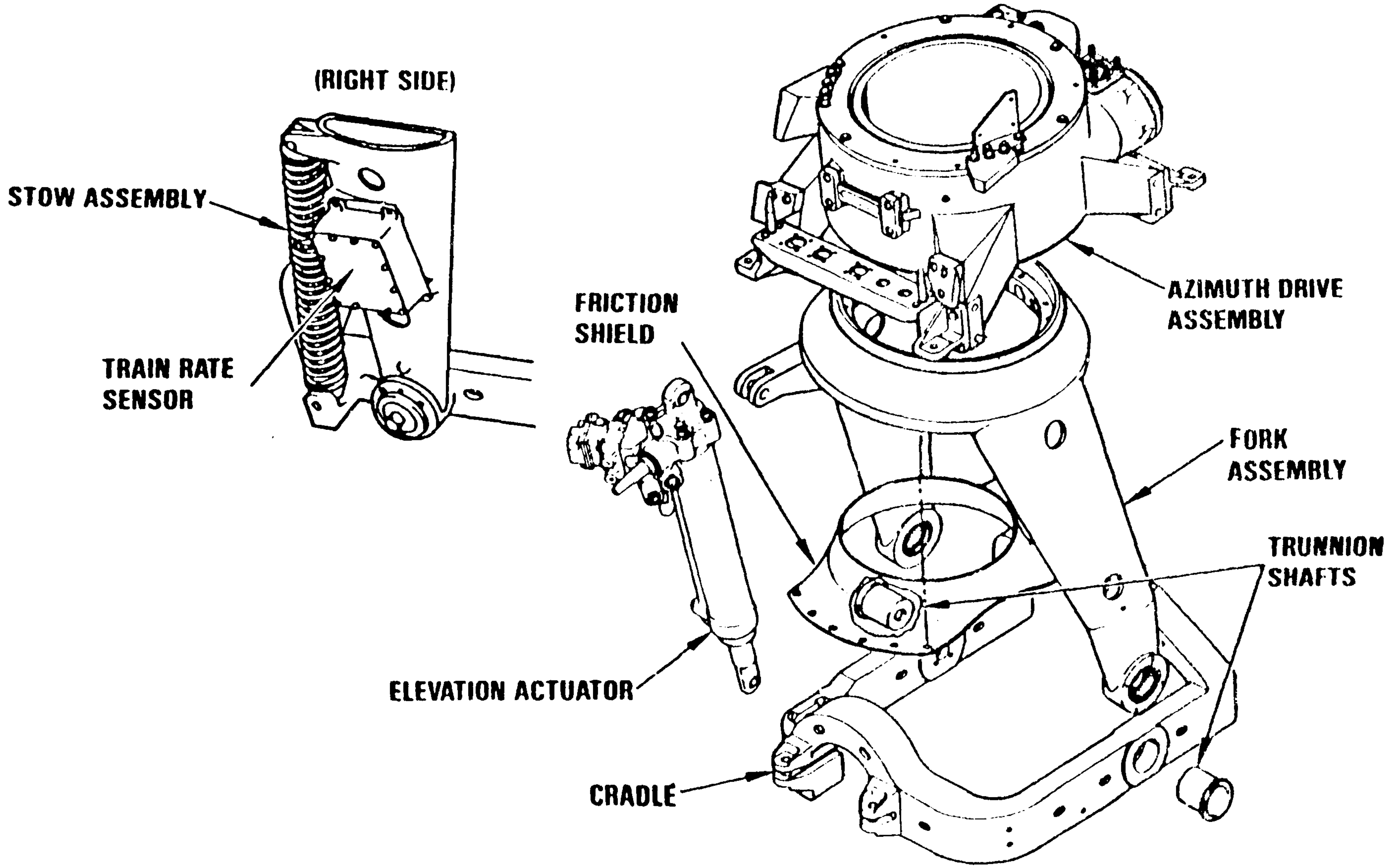


Figure 7. Helicopter gun turret components

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